From Project X to Project Y to Project Z

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XYZ

By LMN

Introduction

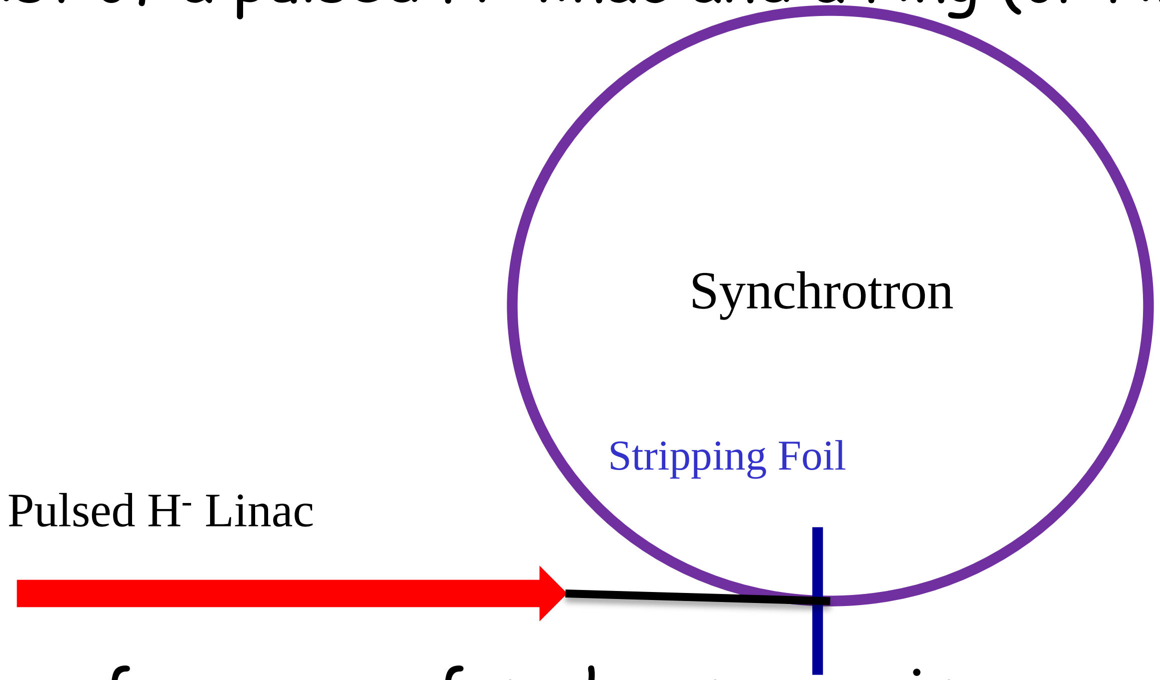
- The future of accelerator-based high energy physics at Fermilab relies on the construction of a high intensity proton source
  - In summer 2007 we proposed Project X (intentionally based on the ILC), 360 kW at 8 GeV
  - May 2008 – P5 report
- Recently, multiple review committees have suggested that Fermilab re-examine the design of Project X
  - The 2007 of ILC-like Project X has evolved into the present ICD (presented by P. Derwent on Oct 30, 2008), 1 MW at 8 GeV
  - Getting ready for a CD0 in Spring 2009

Missions of a new proton source at Fermilab

1. A 2-MW beam from the MI for a long-baseline neutrino oscillation experiments
   - single turn extraction, beam quality unimportant
   - requires 150 kW at 8 GeV
2. Precision experiments at 8-20 GeV with muons and kaons
   - initially, upgrade to Mu2e
   - slow extraction of bunched beams; short bunches
   - 100's kW beams
3. A meaningful first step toward a muon source for a muon collider or a neutrino factory
   - beam power is important (> 4 MW)
   - short bunches on target (beam energy ~20 GeV)
   - rep rate >15 Hz

General configuration

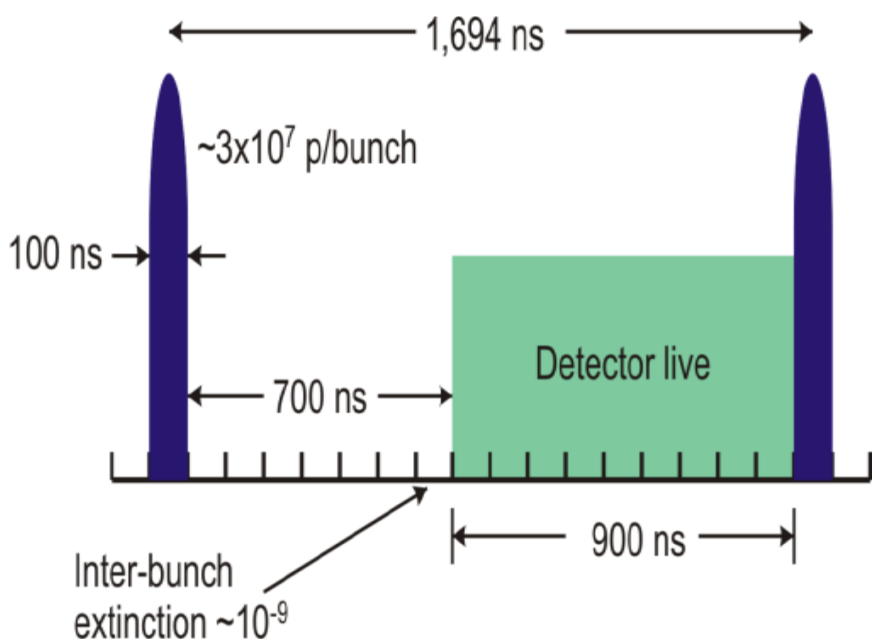
- Any proton source to fulfill these missions will have to consist of a pulsed H- linac and a ring (or rings)



- The performance of such a source is a compromise between
  - The limitations from space-charge tune shift at injection into the synchrotron
  - The high cost of RF power in the linac.

Requirements for the new proton source

- For a 1.4 sec MI ramp cycle, provide 1.6e14 protons in 500 bunches
  - 150 kW beam power at 8 GeV
- Provide additional 100 kW of beam for a Mu2e upgrade
  - Requires repackaging in downstream rings.
- Present Booster can provide 75 kW at most



Space-charge tune shift limits

- The maximum tune shift is limited by how much beam losses one can tolerate
- Fermilab Booster has a tune shift of -0.3 at injection; it looses 15% of particles at injection or 300 W (at 7.5 Hz operation)
- MI has a tune shift of -0.18 at injection (slip stacking); it looses 5% of particles at injection or 1.5 kW

$$\Delta \nu = -\frac{\mathrm{A(N/B)r_p}}{\pi\beta\gamma^2\varepsilon_n}$$

$$\text{Uniform distribution}: A = \frac{1}{2}; \varepsilon_{\mathrm{n}} \text{ is } 100\% \text{ emittance}$$

$$\text{Gaussian distribution}: A = \frac{3}{2}; \varepsilon_{\mathrm{n}} \text{ is } 95\% \text{ emittance}$$

2-MW in the MI

- Project X (both 2007 and 2008 versions) can provide 2-MW beam power in the MI.
- 1.6E14 protons needed for 2 MW correspond to a factor of 3 higher (than present) number of protons per bunch.
  - Very large tune shift if "do nothing"
- The only way to deal with space charge is to use injection tricks
  - Make transverse distribution uniform (by "painting")
  - Make transv. emittance bigger: 15 to 25 μm (100%)
  - Make bunches longer (long. emittance increase, two-harmonic rf)
- Ultimately, no more power upgrades possible without injection energy increase.

Linac utilization

- Linac beam is unusable unless repackaged in rings
- Pulsed Linac (such as Tesla-type) has a very low duty cycle: 1.5 ms at 5 Hz
  - for the Proton source we are interested in average beam power
  - the Linac provides high peak power; but most of the time it sits idle
- We propose that the Linac energy needs to be reduced to take advantage of high duty cycle rf power in a synchrotron ring
- Optimal Linac energy depends on space-charge tune shift limit

Our motivation for an alternative scheme

1. With a present Project X scheme, upgrades beyond 2 MW in the MI are only possible by increasing injection energy:
   - build a new ring or more Linac?
2. Linac is extremely inefficient
   - We pay for high peak power but use average power
3. Can not rebunch beams at 8-GeV in the Recycler because of the space-charge tune shift

- We propose a new proton source consisting of a lower energy linac and a new rapid cycling synchrotron
  - Not same as PD1 or PD2 studies in 2003

Staging

Staged Approach

- The construction of a project in well defined stages in which at the end of every stage a substantial increase in performance is obtained is very attractive in these times of tight budgets.
- This proton source could be built in stages.
  - The first stage is characterized by **an investment in civil construction** and standard accelerator technology.
  - The second stage is characterized in **an investment in more advanced accelerator technology** such as a high energy superconducting linac and a medium energy booster synchrotron.
- This staged approach avoids the "all-or-nothing" pitfalls of the current Project X concept.
  - Technical flexibility
  - Cost

First Stage

- The primary goals of the first stage is to produce
  - A proton beam in excess of 2MW at 120 GeV in the Main Injector for a long baseline neutrino program
  - Provide an 8 GeV proton beam on the order of 100kW to other users
- Space charge tune shift is one of the major intensity limitations for synchrotrons.
  - This is the main motivation for the high energy linac of Project X

First Stage Linac Energy

- The current Fermilab Booster has injection energy of 400MeV and runs a tune shift in excess of 0.3 for an intensity of $5x10^{12}$ protons/cycle.
- If the injection energy was raised to 2 GeV and phase space painting techniques are used, then:
  - intensity of over $38x10^{12}$ protons per batch
  - tune shift less than 0.09
  - 25 π-mm-mrad normalized 95% transverse emittance.
- A 2 GeV Linac is about 280meters long.
  - An 4 GeV Linac is about 400 m long
  - An 8 GeV Linac is about 650 m long
- A 2 GeV linac is only twice the energy of the SNS linac so much of the linac and H- stripping technology used at SNS could most likely be extended to 2 GeV

New Booster

- A new Booster is built following the 2 GeV Linac.
- Booster Size
  - The second stage of this concept proposes raising the extraction energy of the Booster to above the transition energy in Main Injector (~ 20 GeV).
  - Too small of a Booster circumference places severe constraints on:
    - the magnetic field ramp rate;
    - strength of magnetic field
  - Too large of a Booster, increases space charge and cost
  - A reasonable compromise is to have the new Booster circumference one fourth of the Main Injector circumference
- The Booster ramps from 2 GeV to 8 GeV with a cycle rate of 5Hz with a
  - 42% magnet fill factor
  - A ramp rate to 3.6 T/s
  - Peak magnet field 0.48 T

Recycler Accumulation

- The slow cycle rate of 5 Hz is compensated by the use of the Recycler as an accumulation ring following extraction from the Booster at 8 GeV.
  - The main advantage of the Recycler as an accumulation ring is to remove the time it takes to load the Main Injector at injection with multiple Booster batches.
  - Since the accumulation of multiple Booster batches is done at 8 GeV, space charge tune shift in the Recycler is manageable.
  - Even with a Gaussian transverse form factor, the space charge tune-shift is less than 0.07 for four Booster batches in the Recycler at 8 GeV
- The accumulation of four Booster batches at a Booster cycle rate of 5 Hz requires 0.8 seconds of cycle time. This leaves 0.6 seconds of cycle time or three Booster cycles available for other users.

First Stage Parameter Table

Parameter	Value	Units
Linac Beam Current	10	mA
Linac Pulse Length	0.6	mS
Linac Energy	2	GeV
Booster Energy	8	GeV
Booster Circumference	825	m
Booster Cycle Rate	5.0	Hz
Booster Magnetic Field Ramp	3.6	T/s
Booster Magnetic Filling	42	%
Booster Max. Magnetic Field	0.48	T
Booster Batch Intensity	38	$x10^{12}$
Booster Beam Fill	90	%
Booster Normalized Emittance	25	π-mm-mrad
Booster Tune Shift	0.09	
Main Injector Tune Shift	0.07	
Total Cycle Time	1.4	S
Avail. Linac Beam Power	60	kW
Avail. Booster Beam Power	240	kW
120 GeV Beam Power	2.1	MW
Linac-booster duty Factor	57	%

- A 60kW, 2 GeV Linac operating at 5 Hz based on SNS technology.
- H- stripping at 2 GeV based on SNS technology.
- A 240kW, 2 GeV to 8 GeV Booster that is one fourth the size of the Main Injector with a cycle rate of 5 Hz based on 3.6T/s magnet technology.
- Accumulation of four Booster batches at 8 GeV in the Recycler.
- Transfer from the Recycler and acceleration in the Main Injector of $1.5x10^{14}$ protons every 1.4 seconds to provide 2.1MW of beam power at 120 GeV.
- 100kW of beam power at 8 GeV to other users.

Second Stage Motivation

- The first stage achieves Project X goals using straight-forward linac and synchrotron technologies.
- However, a 120 GeV beam power of 2.1 MW is only a factor of three greater than the planned Fermilab Accelerator Nova Upgrade (ANU).
- It could be argued that running the Nova program three times longer might be an alternative strategy.
- It is important that any proton source built at Fermilab have future goals that are at least an order of magnitude greater than ANU

Second Stage

- Because of space charge tune-shift, the only way to increase the Main Injector beam power past 2MW is to increase the injection energy of the Main Injector
- Increasing the injection energy of the Main Injector to 21 GeV
  - Permits a factor 15x more beam current
    - Lower tune-shift & larger aperture
  - Injects above transition in the Main Injector
- To inject more beam current into the Main Injector, the linac energy must be raised.
- A 4 GeV Linac can
  - Provide 2×10^{14} protons/batch (20mA x 1.6ms)
  - 4 GeV Tune shift less than 0.09

Second Stage Accumulation

- The disadvantage of injecting at 21 GeV into the Main Injector is that the Recycler is no longer available for accumulating Booster batches.
- Thus, the Main Injector must hold at the injection energy of 21 GeV while four Booster batches are accelerated and accumulated in the Main Injector.
- This places a premium on Booster cycle time.
  - Loading 4 batches at 15 Hz with a Main Injector ramp time of 1.27 seconds gives a cycle time of 1.53 seconds
  - To run the new Booster at 15Hz,
    - a ramp rate of 31T/sec is required
    - Compared to the present average Booster ramp rate of 22T/sec

Second Stage Parameter Table

Parameter	Value	Units
Linac Beam Current	20	mA
Linac Pulse Length	1.6	mS
Linac Energy	4	GeV
Booster Energy	21	GeV
Booster Circumference	825	m
Booster Cycle Rate	15.0	Hz
Booster Magnetic Field Ramp	30.8	T/s
Booster Magnetic Filling	42	%
Booster Max. Magnetic Field	1.27	T
Booster Batch Intensity	200	$x10^{12}$
Booster Beam Fill	90	%
Booster Normalized Emittance	45	π-mm-mrad
Booster Tune Shift	0.09	
Main Injector Tune Shift	0.04	
Total Cycle Time	1.5	S
Avail. Linac Beam Power	1918	kW
Avail. Booster Beam Power	10071	kW
120 GeV Beam Power	10.0	MW
Linac-booster duty Factor	17	%

- A 1.9 MW, 4 GeV Linac operating at 15 Hz.
- H- stripping at 4 GeV.
- A 10 MW, 4 GeV to 21 GeV Booster that is one fourth the size of the Main Injector with a cycle rate of 15 Hz based on 31T/s magnet technology
- Accumulation of four Booster batches at 21 GeV in the Main Injector.
- Acceleration in the Main Injector of $8x10^{14}$ protons every 1.53 seconds to provide 10 MW of beam power at 120 GeV.
- 1.6 MW of beam power at 4 GeV or 8.3 MW of beam power at 21 GeV to other users.

Cartoon

Design details

Fermilab Booster Experience

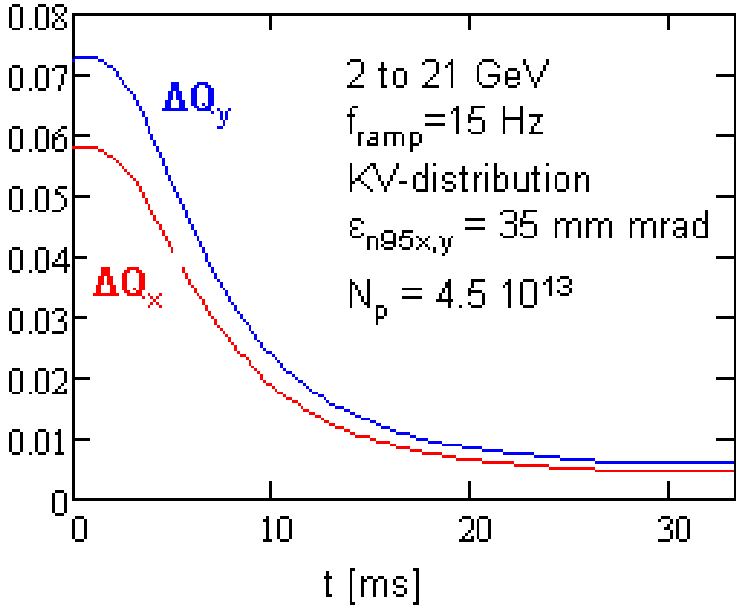
- Present Booster is a good fast cycling synchrotron but…
- We should learn from past mistakes
  - Non zero dispersion in cavities
    - Strong synchro-betatron resonance at injection energy
    - Mitigated by "correct" positioning of cavities along the ring, ~10% left. Optics variations prevent good suppression.
  - Beam directly interacts with steel laminations of dipoles
    - Very large transverse and longitudinal impedancces
  - Instabilities are mitigated by large chromaticity
    - that results in additional beam loss
- Transition crossing
  - Longitudinal emittance growth at transition
- The goal is a 5-fold current increase for Stage 1 compared to present

Limitations on Machine Design

- Space charge tune shift

$$\delta\nu_{SC} = \frac{r_p N_p}{4\pi\beta^2\gamma^3\varepsilon} \frac{C}{\sum L_b}$$

  - Tune shift is 3 times smaller for KV-distribution with the same 95% emittance
  - Steep dependence on beam energy
  - Increase of injection energy reduces required acceptance and, consequently, the ring cost



Limitations on Machine Design (2)

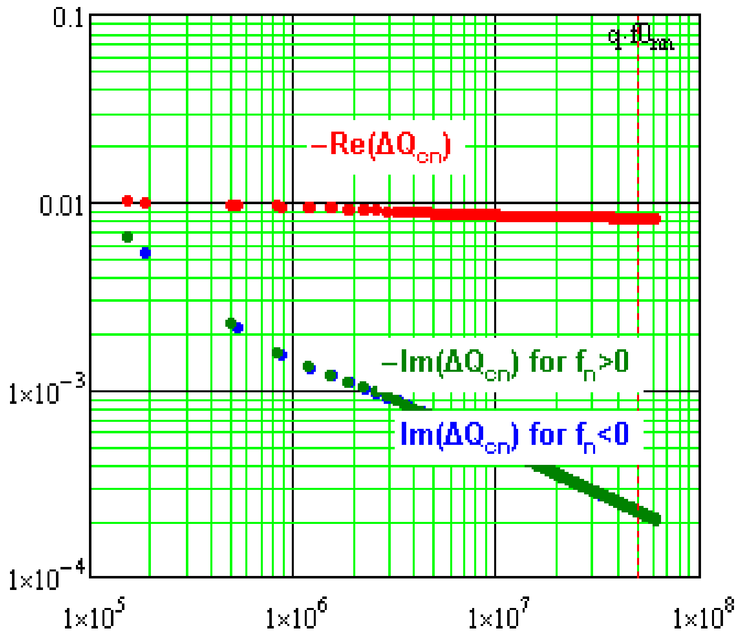
- Transverse instabilities
  - Resistive wall instability is the major offender for RCS
    - Round chamber with thin wall, continuous beam and low frequencies, $\sqrt{ad} > \delta > d$:

$$\mathrm{Im}\left(\delta\nu_{RW_n}\right) = \frac{r_p N_p C^2}{16\pi^4 \beta^2 \gamma \nu (\nu - n)} \frac{1}{\sigma_R a^3 d}$$

  - Strong dependence on circumference, radius and thickness of vacuum chamber

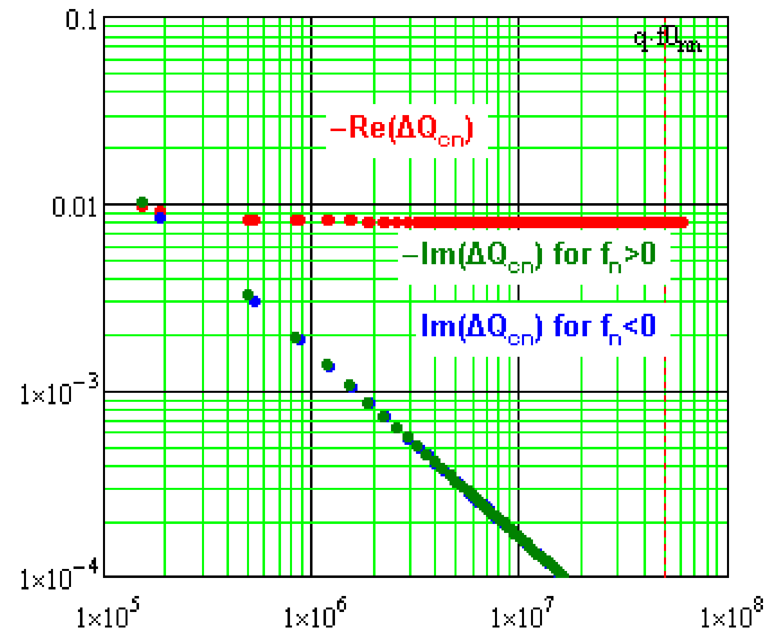
Limitations on Machine Design (3)

Real and imaginary tune shifts for different transverse modes due to wall resistivity, I_{beam}=2.5 A



f [Hz]

Stainless steel vacuum chamber; d=0.7 mm a=2 cm



f [Hz]

Ceramic vacuum chamber with 10 μm copper layer, a=2 cm

Limitations on Machine Design (4)

- Shielding of AC bending field by a vacuum chamber
  - Eddy currents in vacuum chamber result mainly in a delay of bending field

$$\frac{\delta B}{B} = -4\pi^2 ia \frac{\sigma_R ad}{c^2} f_{ramp}$$

    - They do not produce non-linearities if the chamber is round and has constant wall thickness
  - Reduction of shielding increases the transverse impedance

Limitations on Machine Design (5)

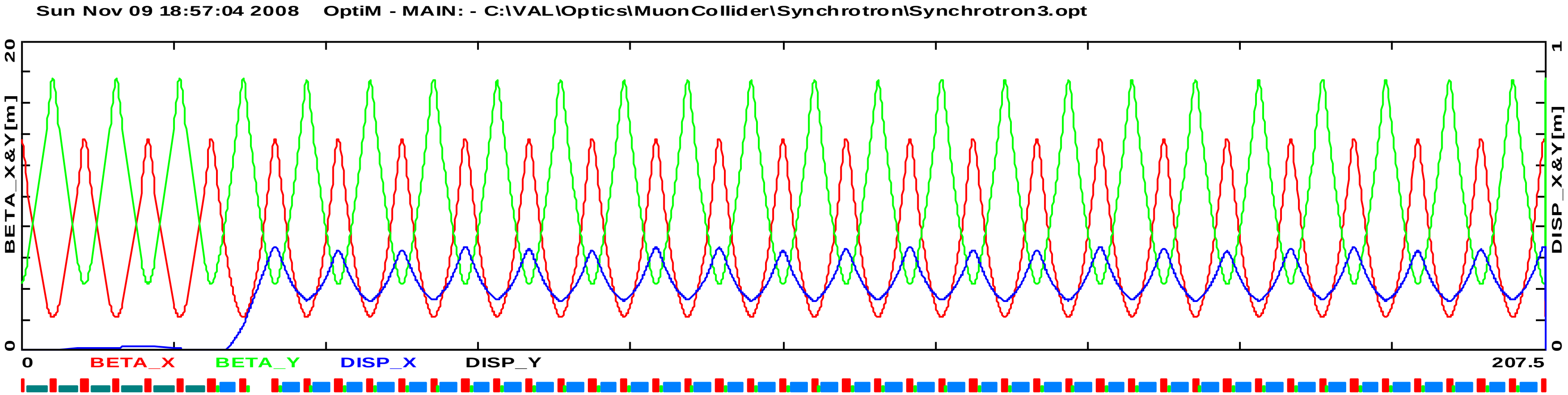
- Heating of the vacuum chamber by eddy currents is more serious technical limitation
  - ➢ The same dependence on vacuum chamber radius and thickness as the growth rate of resistive wall instability

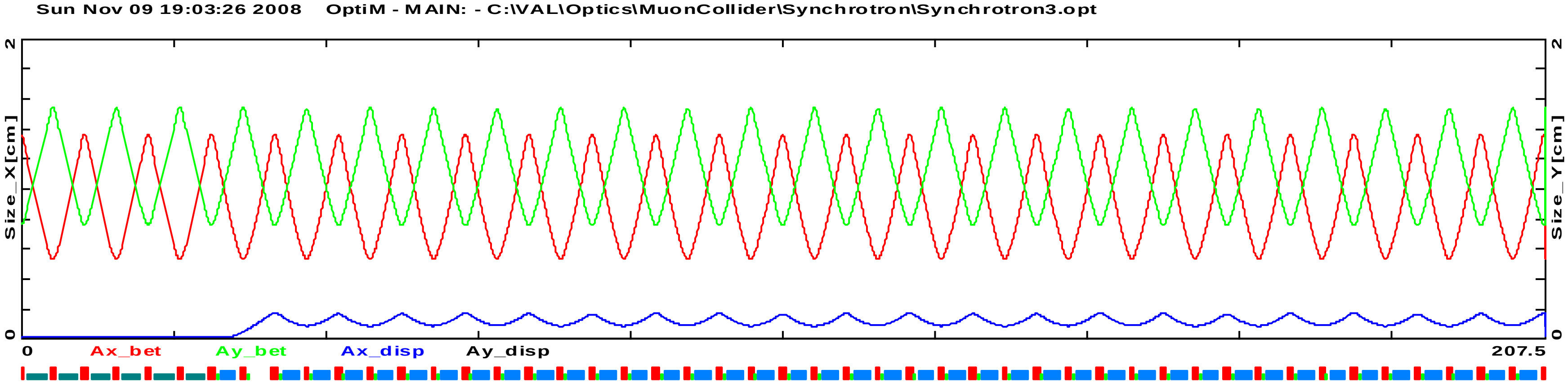
Vacuum Chamber Heating & Shielding
(stainless steel, d=0.7 mm, a=22 mm)

F_{ramp} [Hz]	$\delta B/B$	E_{max} [GeV]	Bmax [kG]	dP/ds [W/m]
5	$3 \cdot 10^{-4}$	8	5.3	3.1
		21	12.5	19
15	10^{-3}	8	5.3	28
		21	12.5	**170**

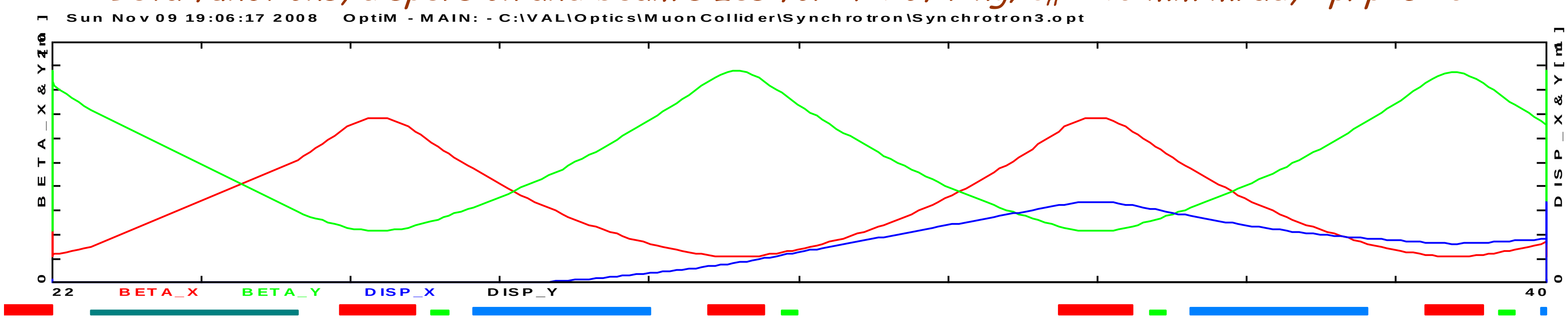
Optics design strategy

- Optics - FODO
  - Racetrack
  - Zero dispersion in the straight lines with a missed dipole
  - Large tune
    - Small momentum compaction
    - Small beam size -> small magnets
- Maximum energy – 21 GeV
  - Between transition energies: E_{MI} =19.3 and E_{RCS}=22.5 GeV
  - Further increase of transition energy would require shortening of dipoles =>larger fields
- Alternative choice of a ring with negative momentum compaction would have
  - larger aperture, larger magnets
  - more problems with vacuum chamber heating
  - more expensive





Beta functions, dispersion and beam sizes for 1/4 of ring; ε_n = 40 mm mrad, $\Delta p/p$=5 10^{-3}



Dispersion is zeroed by missed dipole

Vacuum Chamber

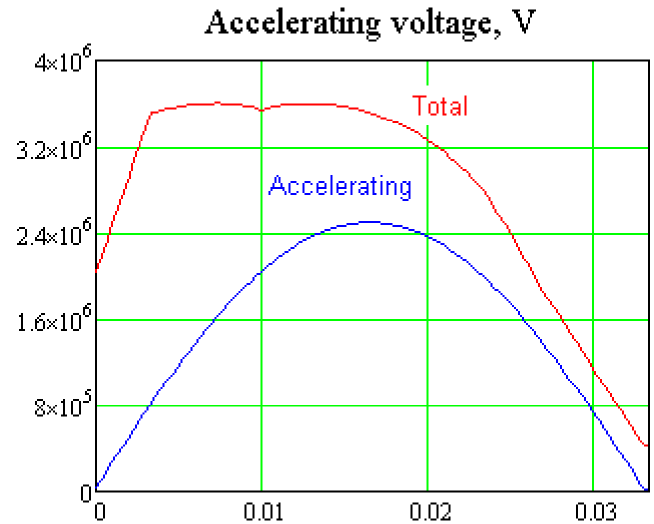
- Choice of Vacuum Chamber
  - Thin wall stainless steel looks very attractive (a = 22 mm, d = 0.7 mm)
    - Inexpensive but
    - Has a problem with its cooling at 21 GeV and 15 Hz
    - However air-cooling looks like a simple and acceptable solution
  - Ceramic with thin copper inside (10 μm)
    - The same heating for the same impedance at lowest betatron sideband !!!
      - But much lower impedance at high frequencies
    - Easier water cooling?
    - Larger total thickness of wall?
    - More expensive, more fragile …

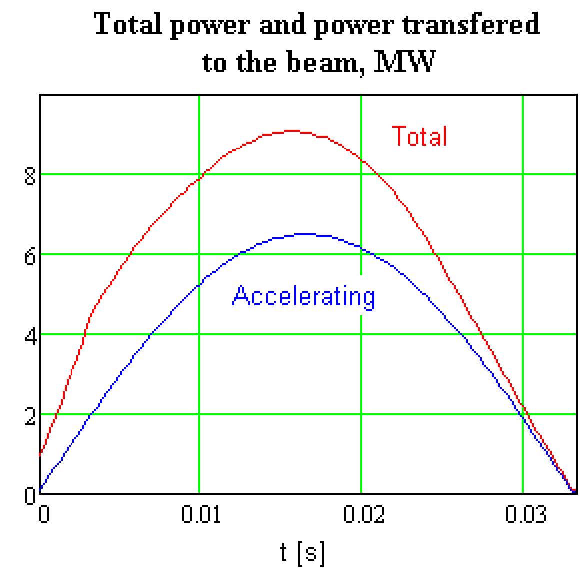
Magnets

- Dipoles (preliminary)
  - 164 rectangular dipoles
  - L=2.13 m, h=46 mm, w=130 mm, 60 turns
    => 27 mH; sagitta = 1 cm
  - At 21 GeV: B=12.5 kG, I=800 A, $P_{average}$=1.5 MW
  - At 15 Hz: Resonance circuit, U_{dipole}=1 kV
- Quads: G=3.1 kG/cm, a=23 mm
  - F quad: L=90 cm
  - D quad L=68 cm
- Sextupoles
  - Natural chromaticity has right sign and correct value
  - Full compensation requires:
    - L=20 cm,
    - S=+0.7 and -0.9 kG/cm^2

- Main RF parameters

	5 Hz, 8 GeV, I_{beam}=2.5 A	15 Hz, 21 GeV, I_{beam}=2.5 A
Total voltage, MV	2.1	3.6
Peak power, MW	1.8	9
Number of cavities	14	24
Shunt impedance, kΩ	100	100
Frequency, MHz	50.3-52.8	50.3-53.1





Main Machine Parameters

	Stage 1	Stage 1a
Injection kinetic energy, GeV	2	2
Extraction kinetic energy, GeV	8	21
Circumference, m	829.8	
γ –transition, γ_t	25.04	
Betatron tunes, Q_x/Q_y	28.42/16.41	
Natural tune chromaticity, ξ_x/ξ_y,	-34/-25	
Norm. acceptance at injection, $\varepsilon_x/\varepsilon_y$, mm mrad	85/65	
Normalized 95% emittance, mm mrad	35	
Harmonic number	147	
Beam current at injection, A	2.5	2.5
Ramp frequency, Hz	5	15
Max. Coulomb tune shifts, KV-distr., $\Delta Qx/\Delta Qy$	0.059/0.072	
RF voltage, MV	2.3	3.6
Beam power, kW	390	2200

Conclusions

Conclusions

- Current Configuration of Project X
  - Is not easily extendable
  - Is inefficient
  - Is risky
- A proton source based on a linac and a rapid cycling synchrotron that can be built in stages
  - Is more flexible
  - Is more efficient
  - Spreads risk
- The design concept of this new proton source is at the same level of maturity as the current Project X ICD
- We should adopt the new concept for the proton source as the basis of CD-0 for Project X